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All measurement values are expressed in the International System of Units (SI) in accordance with NASA Policy Directive 2220.4, paragraph 4.

**ABSTRACT**

The RF radiation produced during intracloud lightning flashes is presented, together with associated fast and slow electric field changes. These data were collected during the Thunderstorm Research International Project in Florida during the summer of 1977. The RF radiation is essentially simultaneous with the fast-field change but has a tendency to peak during the initial half-cycle of the bipolar field changes associated with cloud processes. This is in marked contrast to previous observations of RF radiation during return strokes in cloud-to-ground discharges and provides a clue to the physics of the intracloud discharge.

# RF RADIATION PRODUCED BY INTRACLOUD LIGHTNING DISCHARGES

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## INTRODUCTION

The radio-frequency emissions produced by intracloud lightning are of interest in geophysics because these radiations can be used to infer the location and geometry of lightning channels inside clouds (References 1 through 4) and because these emissions are produced by discharge processes that are not yet well-understood (Reference 5). This paper presents the temporal structure of RF radiation from intracloud processes in conjunction with fast and slow electric field changes, and shows that the RF radiation during large intracloud pulses is substantially different from that during the return stroke portions of cloud-to-ground discharges.

## DATA

All data reported here were obtained at the National Aeronautics and Space Administration (NASA) Kennedy Space Center, Florida, as part of the Thunderstorm Research International Program (TRIP) (Reference 6). The schematic diagram of the experiment shown in figure 1 is substantially the same as that used in the past to monitor RF radiation from return strokes (Reference 7). RF radiation was monitored at several frequencies between 3 and 300 MHz, using tuned radio-frequency receivers manufactured by the Georgia Institute of Technology for the HF band (3 and 30 MHz) and employing commercially available radio receivers (Watkins-Johnson Model WJ-997 and WJ-8730) at frequencies above 50 MHz. Most recording was done at frequencies of approximately 3, 30, 69, 139, and 295 MHz. The 69-MHz channel was a new frequency added for the 1977 season. The fast and slow electric field changes were monitored using an electric field change system similar to that described by Krider *et al.* (Reference 8) and Livingston and Krider (Reference 9). The

bandwidth of the slow field-change system was about 0.2 Hz to 10 kHz, and the bandwidth was about 1 kHz to 2 MHz for the fast field-change system.

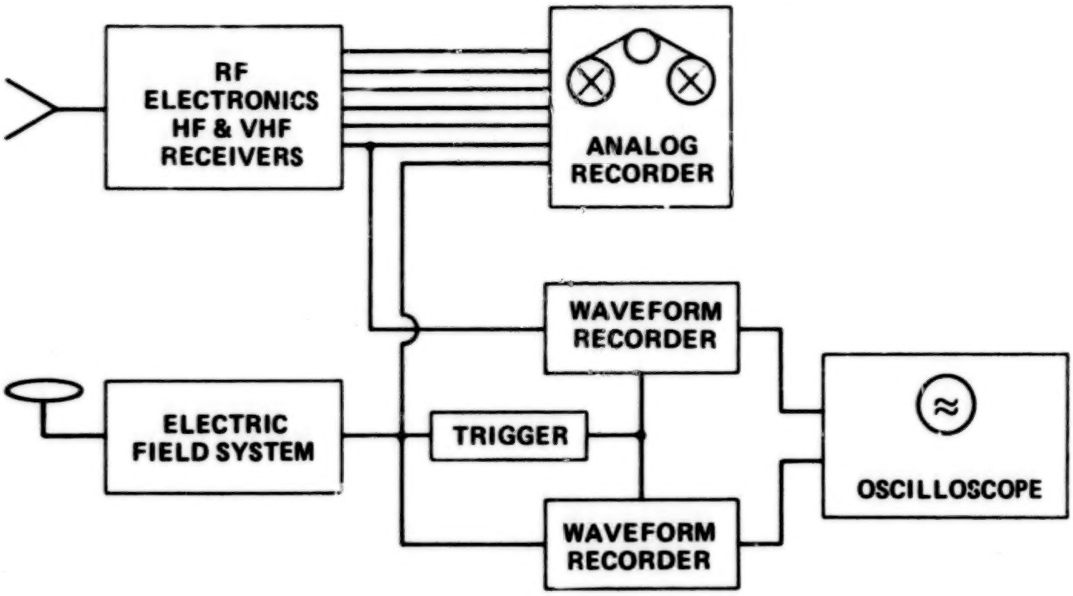


Figure 1. Block diagram of the experiment as performed during TRIP at the Kennedy Space Center, Florida.

The RF radiation and electric field changes were recorded in two modes: continuous analog recording on an instrumentation tape recorder (Ampex PR-2200) and recording at high temporal resolution of selected events using simultaneously triggered sample-and-hold devices (Biomation model 805). The analog recordings provided a continuous record of the RF radiation and electric field changes with a maximum bandwidth of 300 kHz, which was determined by the tape recorder (i.e., 300 kHz for direct record at 60 ips). The data obtained in this mode were used to study radiation patterns on the time scale of the entire flash, for example by displaying the data on high-speed strip charts. On this time scale (resolution of 10's of milliseconds), the RF radiation from lightning is a sequence of impulses. Each impulse corresponds to radiation from individual events in the flash (such as return strokes, leader steps, K changes, etc.), but, because of the low temporal resolution, only an indication of relative intensity is available, not details of the temporal structure.

An example of data recorded in this mode, together with the associated slow electric field change, is presented in figure 2 for radiation from an intracloud flash, and an example of the radiation associated with a cloud-to-ground flash is shown in figure 3. These figures present the RF data on a linear amplitude scale corrected for relative differences as a function of frequency. Thus, the impulses at 295 MHz, which appear to be about the same as those at 3 MHz, are actually about 2 orders of magnitude less in amplitude. Both the slow electric field changes and the RF radiation are characteristic of the flash type (References 10 and 11) and were used in this work to identify flash type.

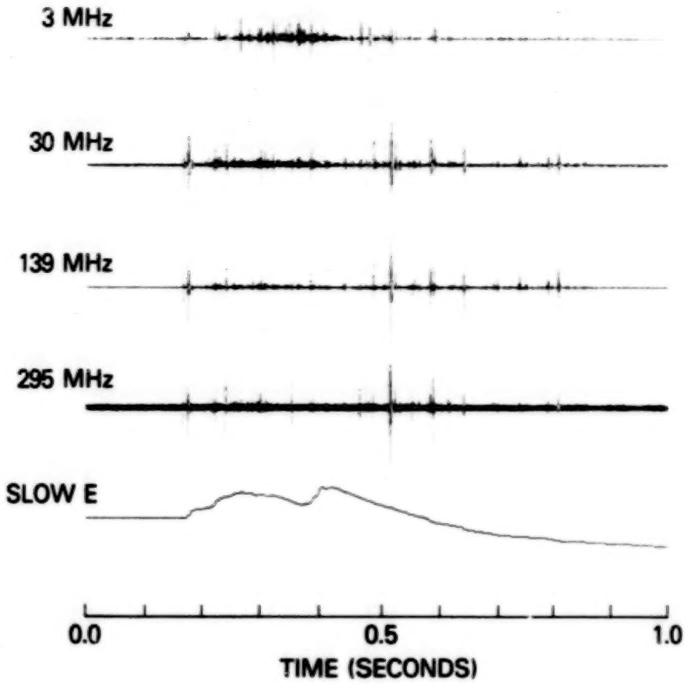


**Figure 2. Example of RF radiation from an intracloud flash. All RF data are vertically polarized.**

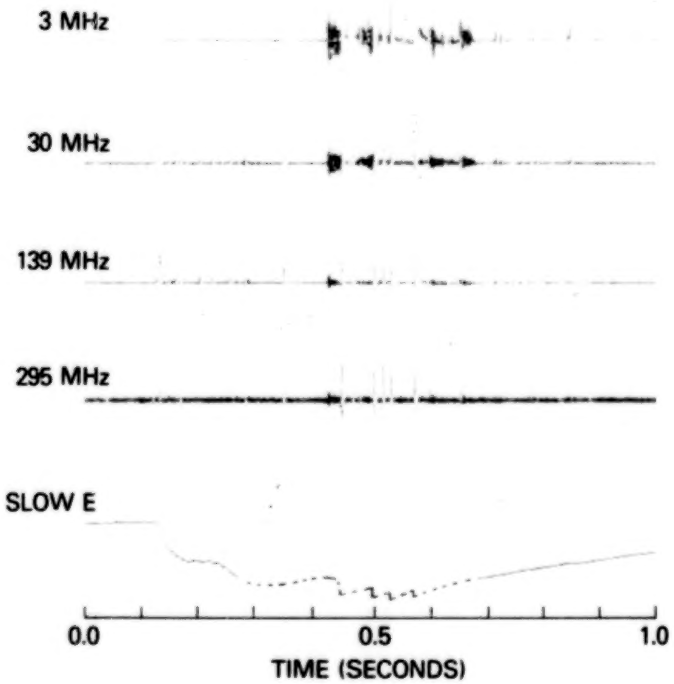


**Figure 3. Example of a cloud-to-ground flash in which prestroke intracloud radiation is apparent.**

The high temporal resolution required for examining the detail of individual events within the flash was obtained with the second mode of data recording. In this mode, several Biomation waveform recorders (sample-and-hold devices) were used to simultaneously record RF radiation and fast field changes. The recording system is similar to that described by Krider *et al.* (Reference 8) and Le Vine and Krider (Reference 7). In particular, several Biomation model 805 waveform recorders were operated in the pretrigger mode, which permits events to be recorded within a selectable time window both before and after the trigger event. The waveform recorders were triggered by the fast field-change system, and the stored waveforms were then displayed on an oscilloscope and photographed (figures 4 through 7). Great care was taken to ensure that all data were displayed with precise time synchronization so that the development of RF radiation (upper traces) and the fast electric field changes (lowest trace) could be compared.

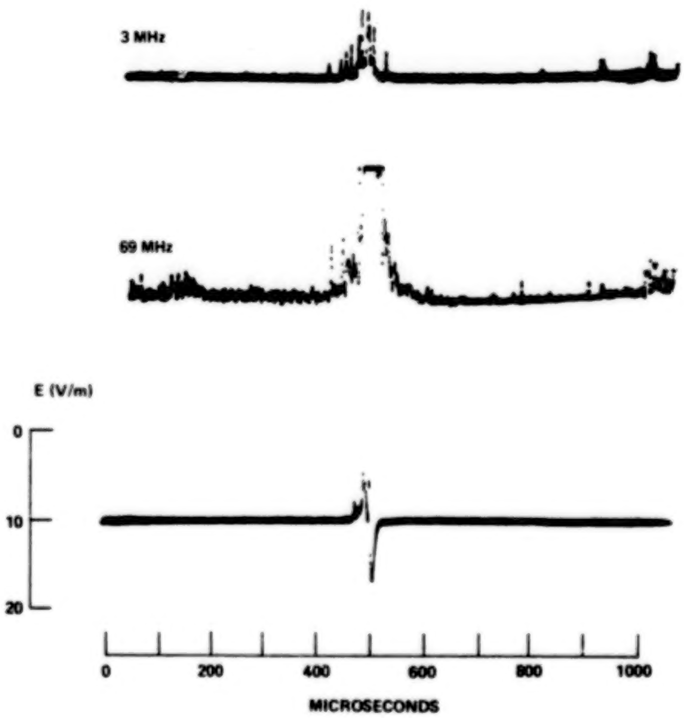


Figure 4. The RF radiation at 3 and 69 MHz and the fast electric field change produced during an intracloud lightning discharge.

Both the continuous analog recording (tape recorder) and high time-resolution recording (waveform recorders) were run simultaneously. Thus, it was possible to associate low resolution data such as that shown in figures 2 and 3 with records of selected events such as those in figures 4 through 7. In this manner, the flash type could be determined for selected events; however, the time base was not sufficiently detailed to permit correlation of the individual event records with a particular impulse in the low-resolution records such as those

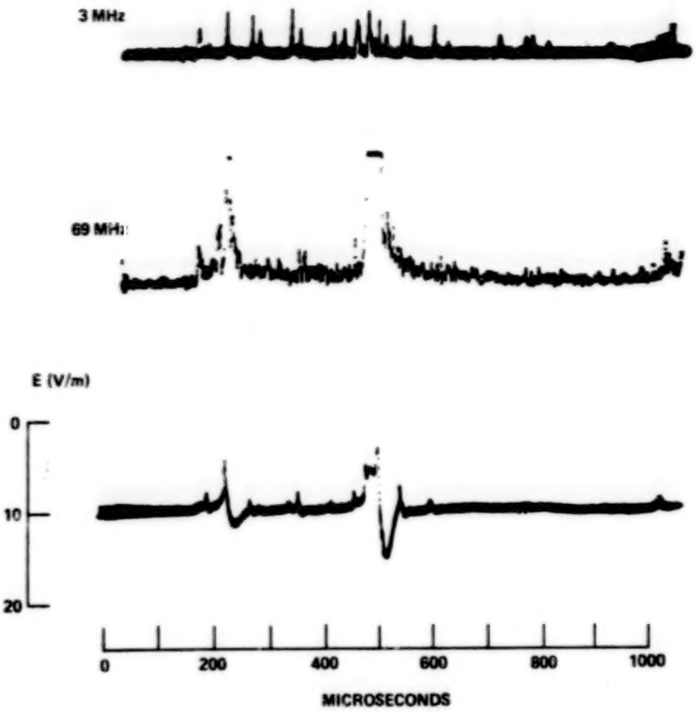


Figure 5. An example of RF and fast electric field change during a sequence of events from an intracloud discharge.

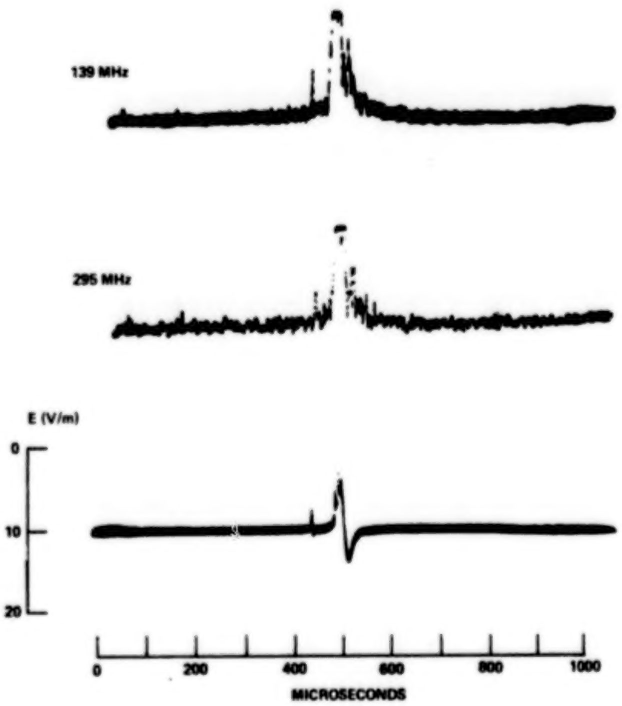


Figure 6. The RF radiation at 139 and 295 MHz and the associated electric field change during an intracloud discharge.

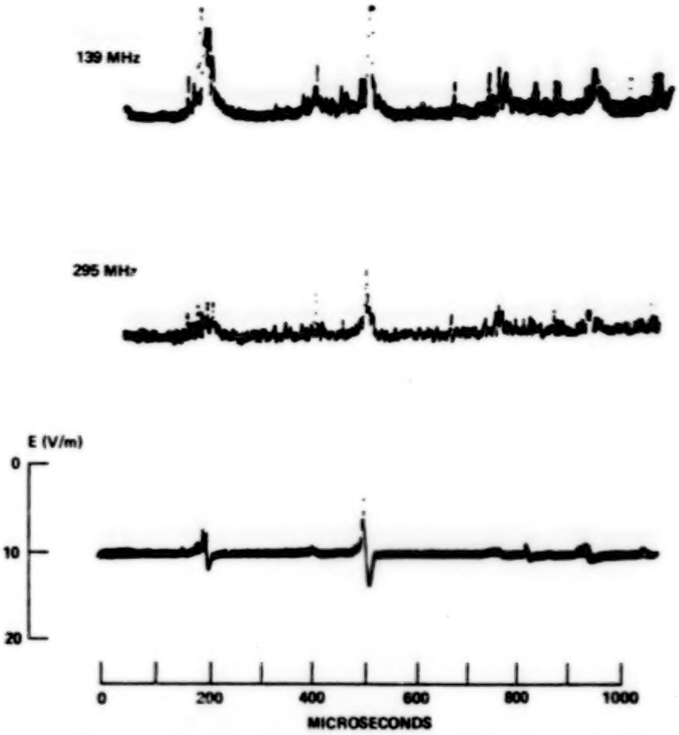


Figure 7. A comparison of RF radiation at 139 and 295 MHz and electric field change as in figure 6 except that, in this case, it occurs as a sequence of events during an intracloud discharge.

in figures 2 and 3. For purposes of this document, flashes were separated into events associated with isolated intracloud flashes such as those in figure 3 which contain no return strokes, and cloud-to-ground flashes such as those in figure 2, which may have detectable intracloud radiation preceding and/or after the first return stroke. All data discussed here came from isolated intracloud flashes. This separation ensures that the individual events under investigation are cloud processes.

## DISCUSSION

The fast electric field changes associated with intracloud processes have been discussed in detail by Weidman and Krider.* Large pulses can occur either as a precursor to a cloud-to-ground flash (figure 3) in which the initial polarity of the pulse tends to be positive or as part of an isolated intracloud flash (figure 2) in which the initial pulse polarity is usually

*C. D. Weidman and E. P. Krider, "The Waveforms of Radiation Fields Produced by Intracloud Lightning Discharges," to be published in *J. Geophys. Res.*

negative. The examples shown in figures 4 through 7 are all from isolated intracloud flashes and are reasonably representative of this class of field change (negative is up). Note that all electric field changes tend to be bipolar with several fast, almost unipolar pulses superimposed on the initial half-cycle. Weidman and Krider* have suggested that the fast pulses are associated with the formation of the channel in a stepped fashion, similar to the dart-stepped leader in cloud-to-ground lightning and that the bipolar field is casued by a slow current surge. Similar pulse shapes can also be produced by recoil streamers on abruptly terminated tortuous channels without having to assume superimposed fast and slow current pulses (Reference 12). The field changes associated with these intracloud flashes tend to occur as single events (figures 4 and 6) or in clusters (figures 5 and 7). Examples of both types have been included, and no readily apparent differences have been found in either the electric field changes or RF radiation.

Figures 4 through 7 show that each cloud event is associated with a simultaneous burst of RF radiation at all frequencies. As far as we have been able to determine, the RF radiation is simultaneous with the electric field change (E), although it tends to reach a maximum during the negative-going initial half-cycle of the associated field change (especially apparent in figure 6). This is the side on which the superimposed short pulses are found.* The duration of the RF radiation tends to be somewhat longer than the electric field change, although this is probably an effect of relative detector sensitivity.

The near simultaneity of the RF radiation and the fast electric field change during large intracloud events is especially important because it contrasts greatly to the time evolution of RF radiation during return strokes in discharges to ground (References 7, 13, and 14). For example, the RF radiation during first return strokes in Florida usually rises to maximum intensity in 10 to 30 microseconds after the onset of the fast electric field change (Reference 7). During subsequent return strokes, the RF radiation begins several hundred microseconds before the onset of the fast field change and is usually absent during the return stroke itself (References 1 and 7). In contrast, RF radiation during intracloud events appears to be nearly simultaneous with the electric field change.

These dramatic differences in the RF radiation suggest interesting physics in the cloud. Unfortunately, the physics governing radiation from lightning at radio frequencies is not yet completely understood (Reference 15). One possible explanation suggested by the data is that the RF radiation is linked to the breakdown process. For example, Proctor has recently found that emissions near 50 MHz often appear in regular sequences or bursts of pulses with a repetition frequency either near 2 kHz or in the range from 30 to 500 kHz (References 1 and 2). By using a time-of-arrival locating technique, Proctor was able to determine that the source of the 2 kHz RF bursts propagate in a regular sequence and suggested that these

*C. D. Weidman and E. P. Krider, "The Waveforms of Radiation Fields Produced by Intracloud Lightning Discharges," to be published in *J. Geophys. Res.*

pulses are produced at the tips of breakdown streamers. This picture is consistent with our present measurements, which indicate that the RF radiation tends to peak during the initial half-cycle of the intracloud pulses during which the leader-like pulses, and therefore breakdown, occur. Such an hypothesis would be consistent with the lack of RF radiation during subsequent return strokes, but has difficulty with the RF radiation associated with first return strokes.

An alternate point of view is that RF radiation and fast electric field changes are manifestations of the same electrical processes; their different characteristics are, under this hypothesis, a consequence of the receiving system used to monitor the radiation (e.g., different bandwidth, center frequency, type of detector, etc.). This is an hypothesis that Le Vine and Meneghini have pursued using as a model "process" current pulses propagating along tortuous channels (Reference 12). The fundamental idea follows from a well-known result in traveling-wave antenna theory that radiation from a current filament driven by a traveling current pulse radiates as if the fields emanated from the filament ends (References 16 through 18). Uman *et al.* applied this result to radiation from lightning return strokes, but without consideration of channel tortuousity (Reference 4). In a model that includes tortuosity, radiation occurs from each point at which there is a change in direction and with an intensity that is dependent on the magnitude of the change. The net effect in the case of first return strokes is, in the time domain, an electric field change representative of observations (Reference 12) and, in the frequency domain, improved agreement between the transmission line model and spectral measurements from lightning (References 19 through 21). By assuming a change in the scale of tortuosity near the cloud base, Le Vine and Meneghini* have been able to obtain time delays in the RF radiation from first return strokes that are consistent with observation (i.e., about 20 microseconds) and could obtain intracloud field changes as described in this document by assuming that they result from recoil streamers on abruptly terminated, tortuous channels.

Regardless of what one is inclined to believe concerning radiation at RF, it seems clear that patterns in the radiation such as those reported here and in previous work (References 7 and 13) provide important clues for understanding the radiation processes in lightning. The authors hope to be able to test their typothesis with future experiments during the development of individual storms under a variety of meteorological conditions. For example, because the characteristics of electric breakdown in air are a function of the electric field, the ambient pressure, and the presence of various types of cloud particles, it is likely that the characteristics of the breakdown and RF sources will depend on the location within the cloud and on the stage of the storm development.

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*Unpublished data.

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